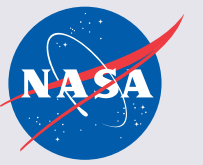


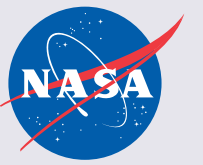
A satellite map of North America, showing the United States and Mexico. The map is overlaid with a green grid pattern and several red diagonal lines. The word 'Mexico' is visible in the upper right corner.

# The Carbon Balance Observatory (CARBO) Instrument for Space-based Observation of Greenhouse Gases

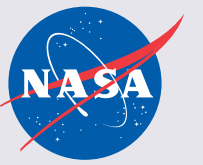
Shannon Kian Zareh, Charles E. Miller, J. Kent Wallace  
Jet Propulsion Laboratory, California Institute of Technology  
ESTF2019 Meeting, NASA Ames  
13 June 2019



- Charles Miller (PI)
- J. Kent Wallace
- Yuri Beregovski
- Mayer Rud
- Randy Bartos
- Jim McGuire
- Tom Pagano
- Dan Wilson
- Cynthia B. Brooks – UT Austin
- Dan Jaffe – UT Austin
- Andre Wong
- Didier Keymeulen
- Peter Sullivan
- Elliott Liggett
- Michael Bernas
- Amy Mainzer
- Annmarie Eldering
- Dejian Fu

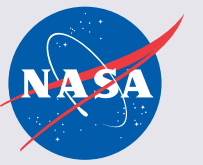


- Programmatic overview
- CARBO instrument concept
- Instrument architecture
- Key technologies
  - Immersion gratings
  - Polarization sensing
  - Large format CHROMA-D/GeoSnap focal plane arrays
- Instrument radiometric performance estimate
- Summary and conclusion



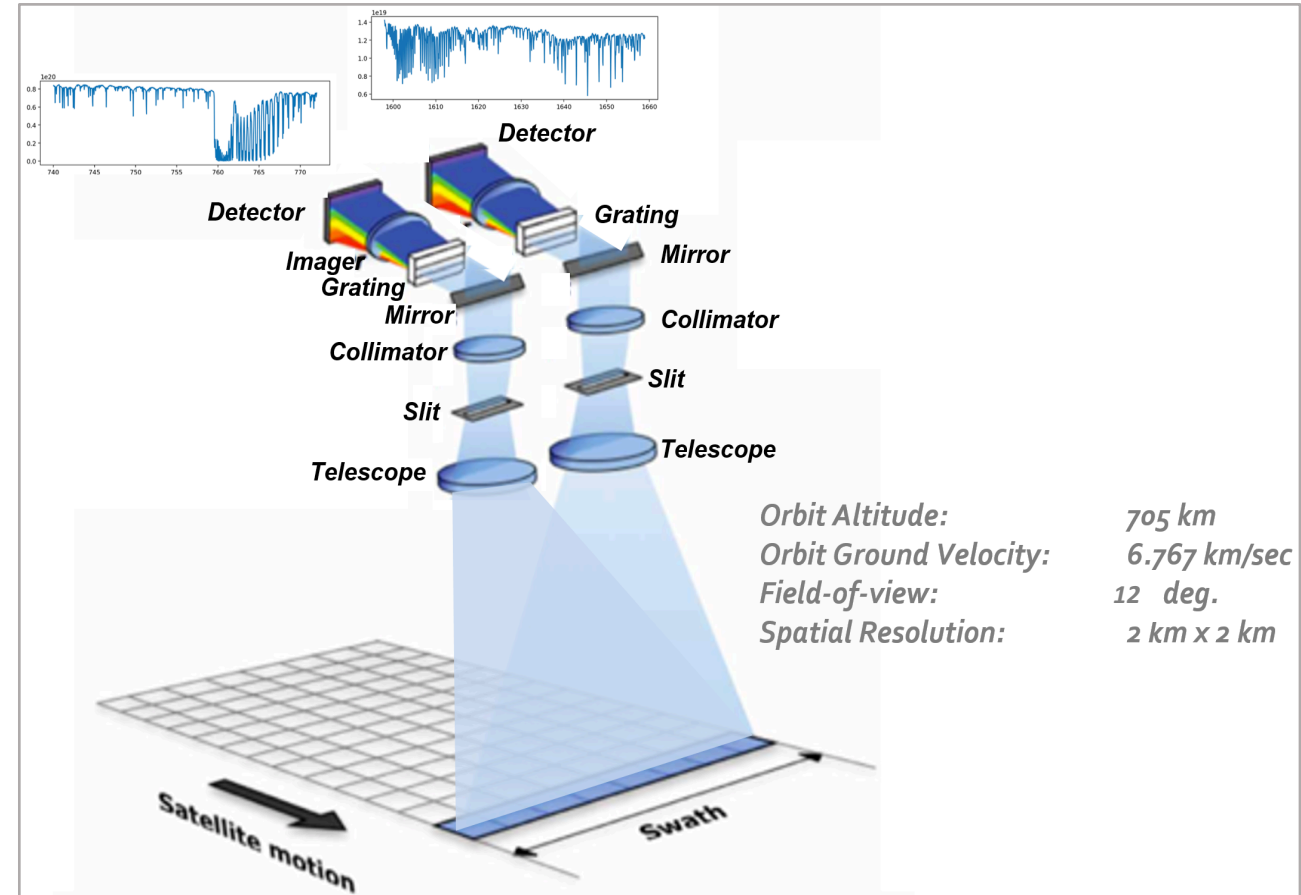
- Funded by Instrument Incubator Program (IIP)
  - NASA's Earth Science Technology Office (ESTO)
- Institutions:
  - Jet Propulsion Laboratory
  - University of Texas at Austin
  - Caltech
- Goal:
  - Develop a new, more capable suite of instruments to measure the green house gasses for better understanding of carbon climate.
  - Advance new technology immersion gratings and modular instrument architecture.

# CARBO Instrument Concept




- Wide-FOV imaging spectrometer
  - FOV: 12 degree with 2k x 2k Geosnap
  - Ground swath: 148 km
- Low Earth orbit (LEO)
- Spatial resolution of 2 km x 2 km
- Weekly revisit rate
- Contiguous spatial sampling
- Adds CH<sub>4</sub> and CO to the CO<sub>2</sub> and Solar Induced Fluorescence (SIF) measurements pioneered by the Orbiting Carbon Observatory (OCO-2/3)
  - increases ability to disentangle carbon fluxes into their constituent components
- Modular architecture
- New technology
  - Immersion grating
  - CHROMA-D/GeoSnap focal plane array: a large-format, low-noise detector optimized for imaging spectroscopy
  - Polarization sensing

13 June 2019



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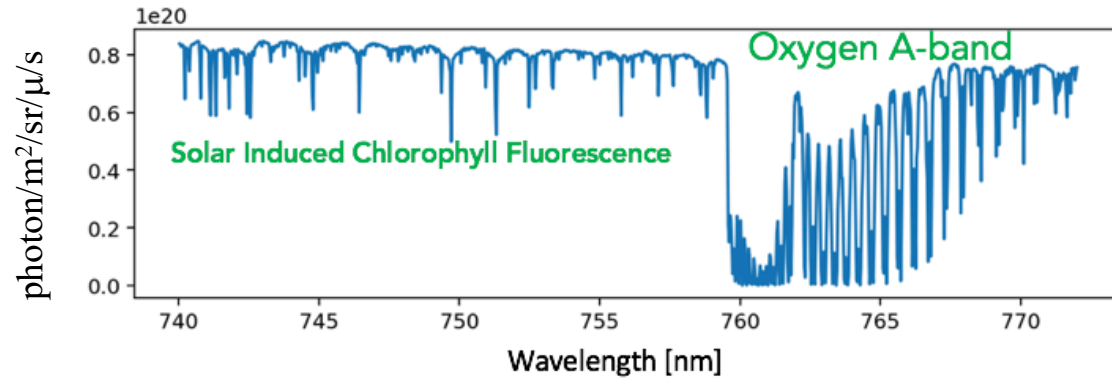
# CARBO Design Requirements

CARBO Requirements	Design, Build, Field Test		Design	
	Instrument 1	Instrument 2	Instrument 3	Instrument 4
<b>Spectral Range (nm)</b>	745 - 772 ( $\Delta\lambda = 27$ nm)	1598 – 1659 ( $\Delta\lambda = 61$ nm)	2045 – 2080 ( $\Delta\lambda = 35$ nm)	2305 – 2350 ( $\Delta\lambda = 45$ nm)
<b>Measurement Targets</b>	O <sub>2</sub> , SIF	CO <sub>2</sub> , CH <sub>4</sub>	CO <sub>2</sub>	CO, CH <sub>4</sub>
<b>SNR @ 5% albedo and 50° SZA</b>	> 300	> 350	> 150	>100
<b>Spectral resolution FWHM (nm) at <math>\lambda_{ave}</math></b>	0.05	0.15	0.10	0.12
<b>Spectral Resolving power at <math>\lambda_{max}</math></b>	15,440	11,060	20,800	19,583
<b>Required Precision</b>	 $X_{CO_2} < 1.5$ ppm, $X_{CH_4} < 7$ ppb, $X_{CO} < 5$ ppb, SIF < 20%			

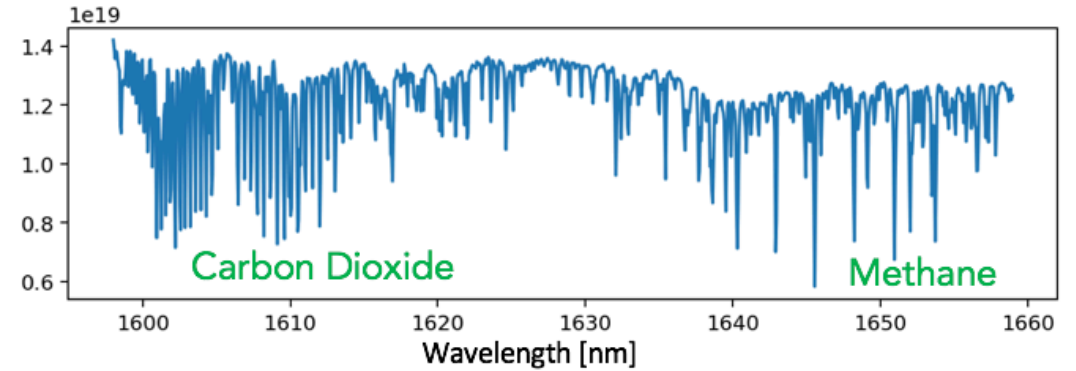
- Nominal bright case – SNR @ SZA = 35 deg and albedo = 30%
- The SNR case for SZA = 50 deg and 5% albedo is the driving/limiting dark case

# Simulated CARBO Instrument Performance

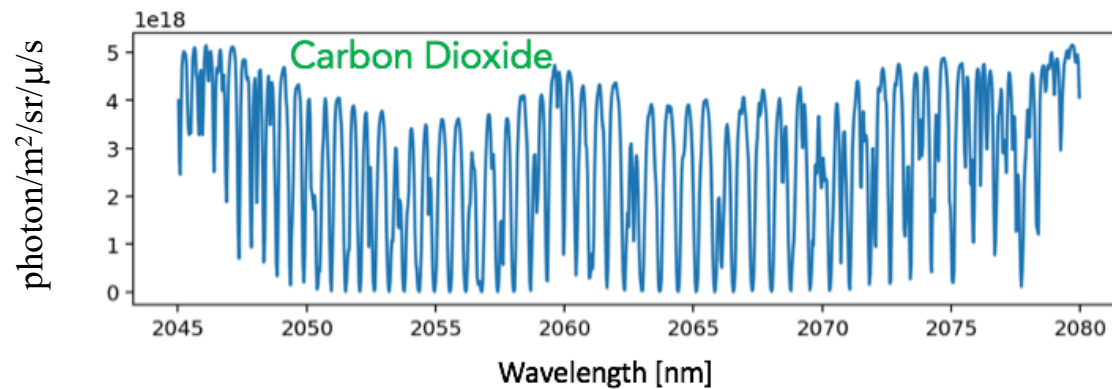
## Instrument 1



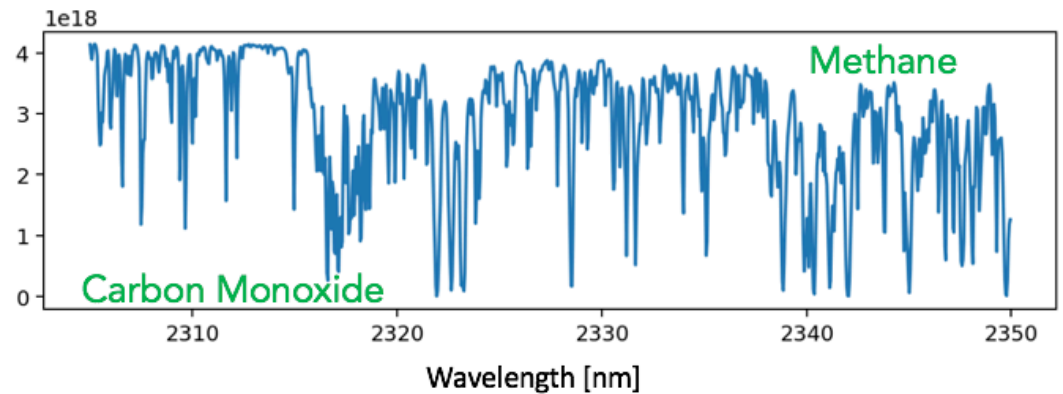
## Instrument 2



## Instrument 3



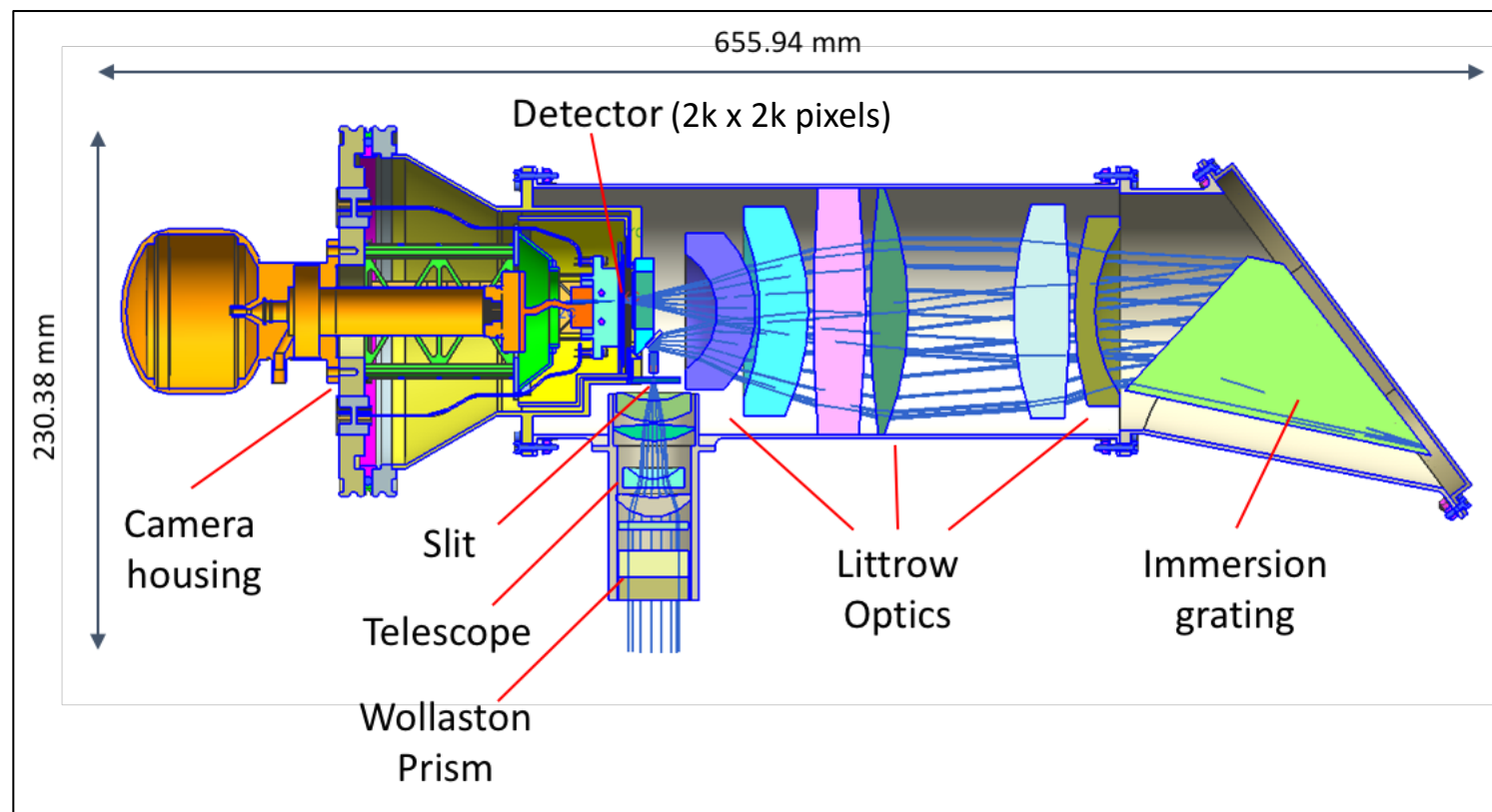
## Instrument 4



## Instrument 1

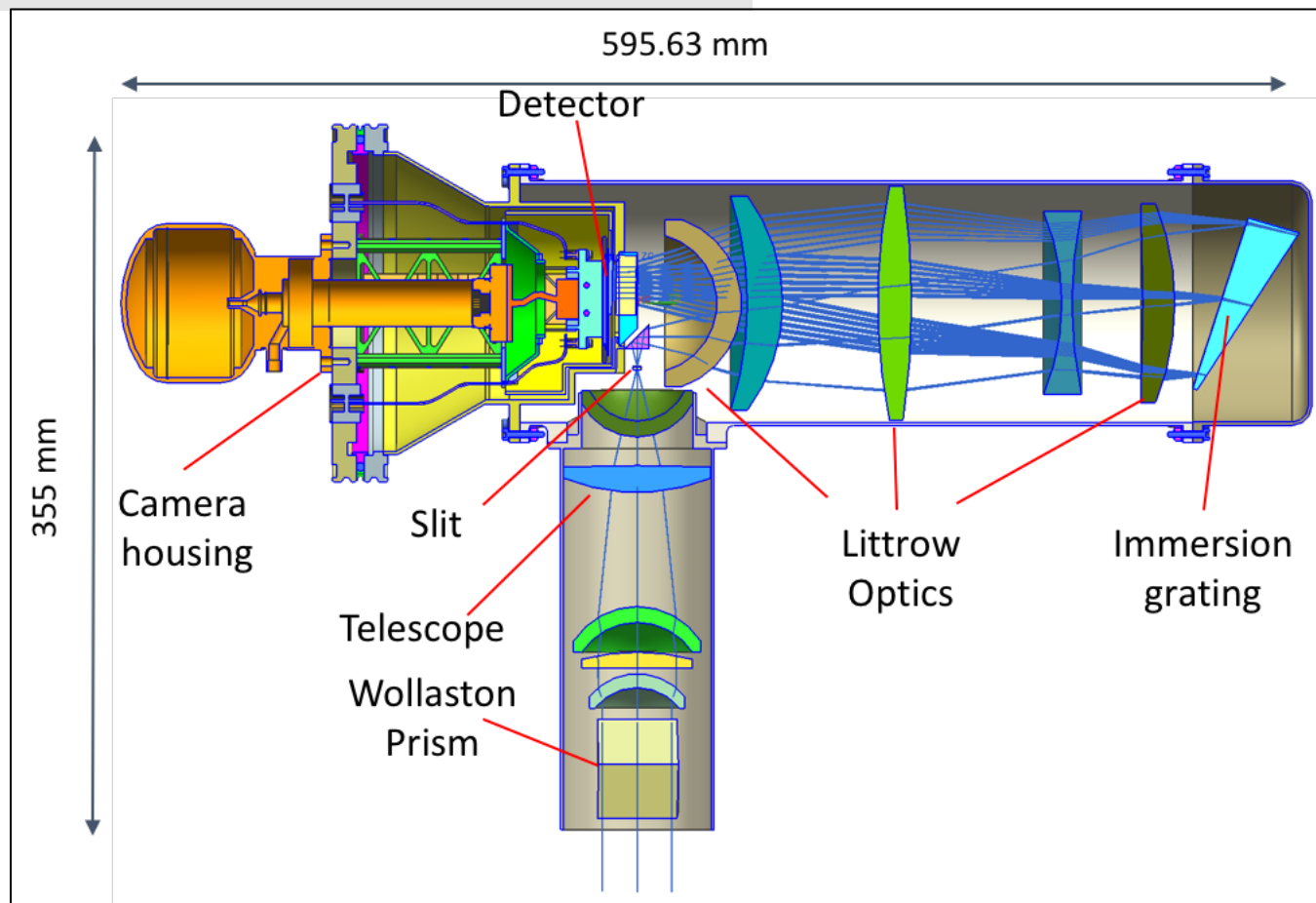
*(745 – 772 nm, Oxygen-A band and SIF Remote Sensing)*

- Telescope aperture diameter: 25 mm
- Telescope focal length: 52.8 mm
- Telescope F/# : 2.11
- Ground Sample Distance: 240 m
- Slit width: 36  $\mu\text{m}$
- Wavelength range : 27 nm
- Spectral Resolution: 0.05 nm
- $R = 15,400$
- Spectral dispersion: 1080 pixels



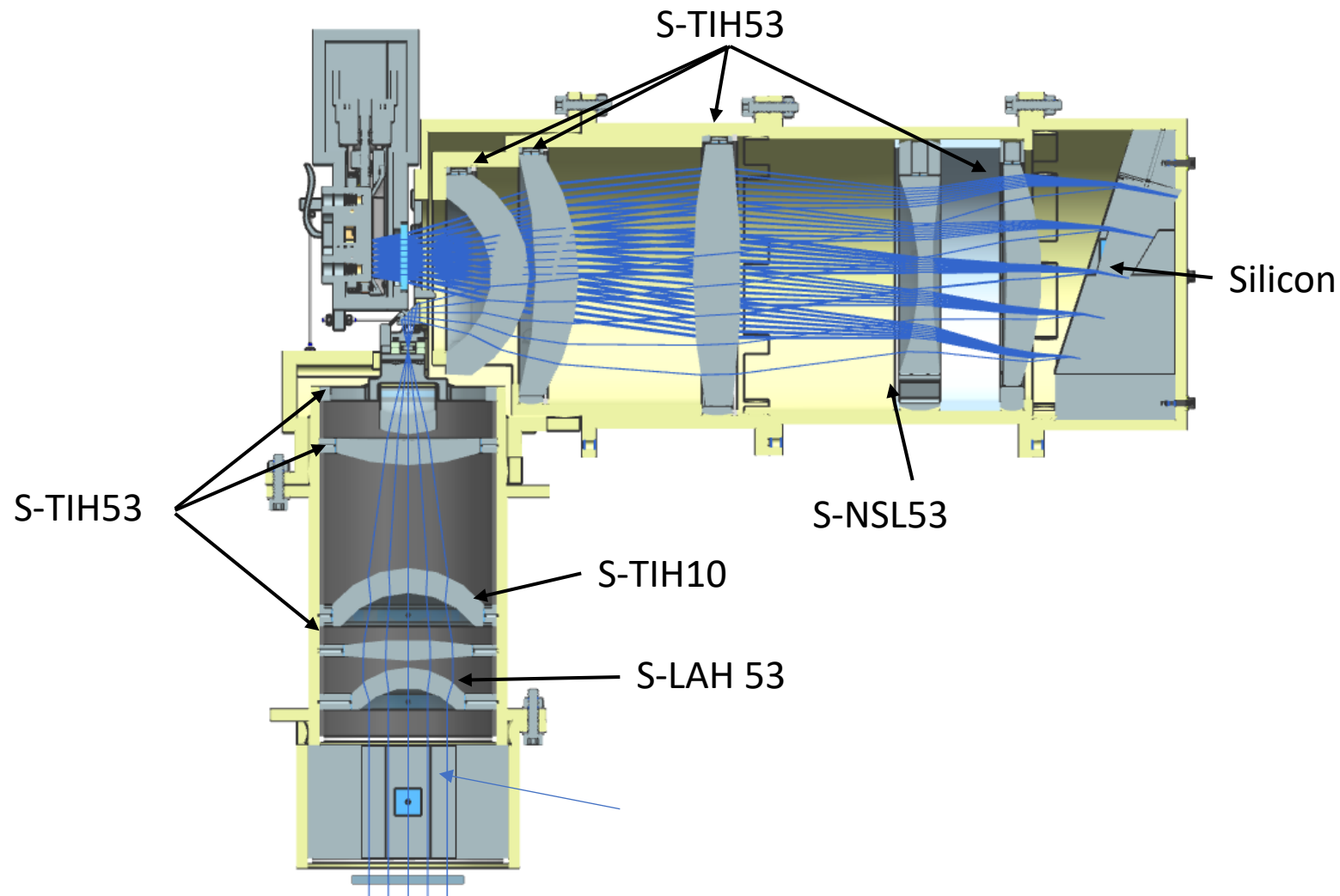
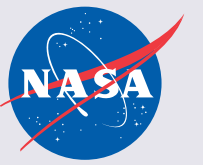
## Instrument 2 (1595 – 1659 nm, CO<sub>2</sub> and CH<sub>4</sub> Remote Sensing)

- Telescope aperture diameter: 35 mm
- Telescope focal length: 75.18 mm
- Telescope F/# : 2.11
- Ground Sample Distance: 168 m
- Slit width: 36  $\mu$ m
- Wavelength range: 61 nm
- Spectral Resolution: 0.15 nm
- R = 11,060
- Spectral dispersion: 814 pixels



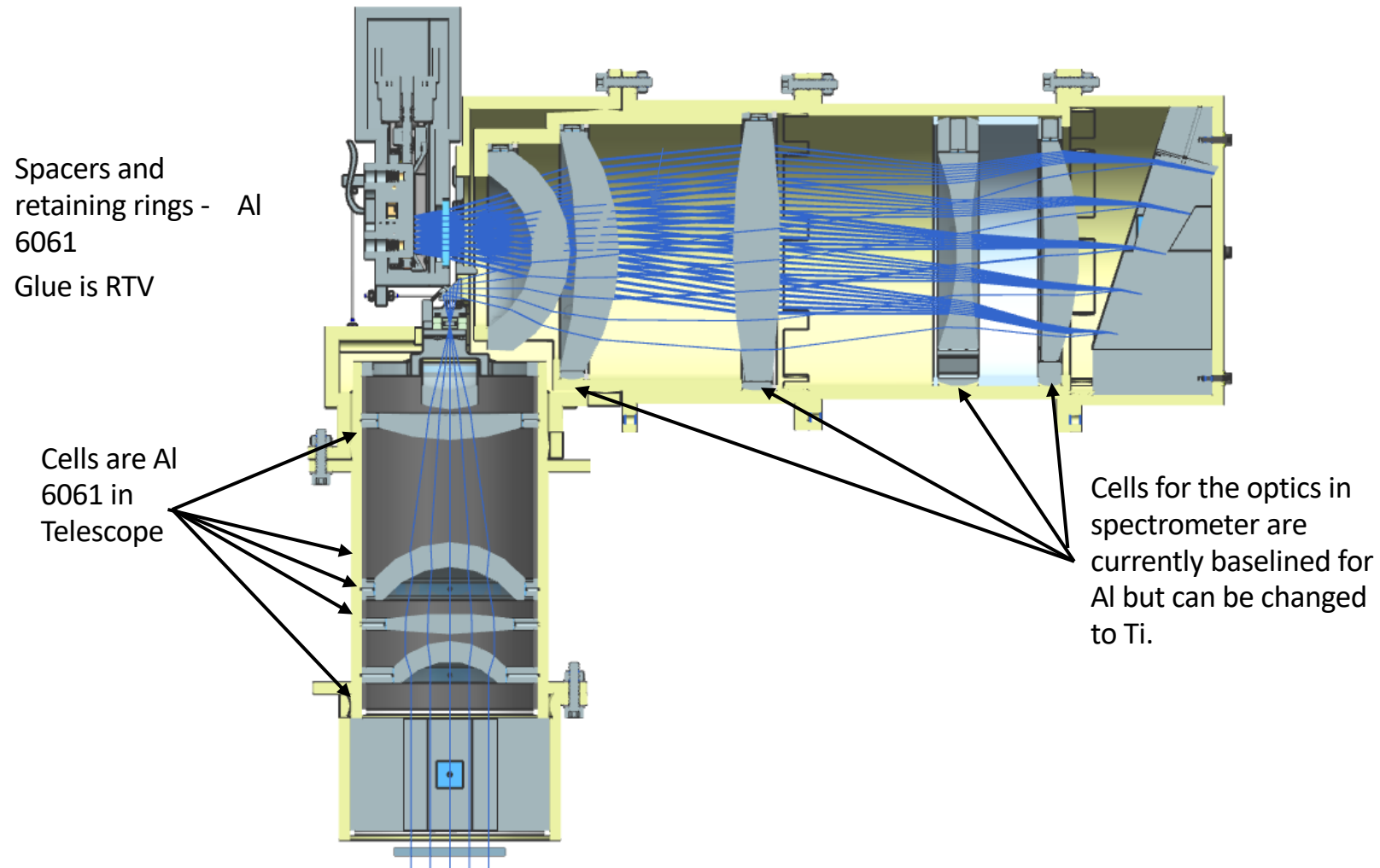
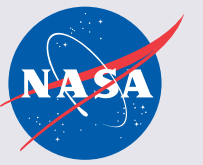
# Instrument 2

## Optical Design & Optomechanical Packaging

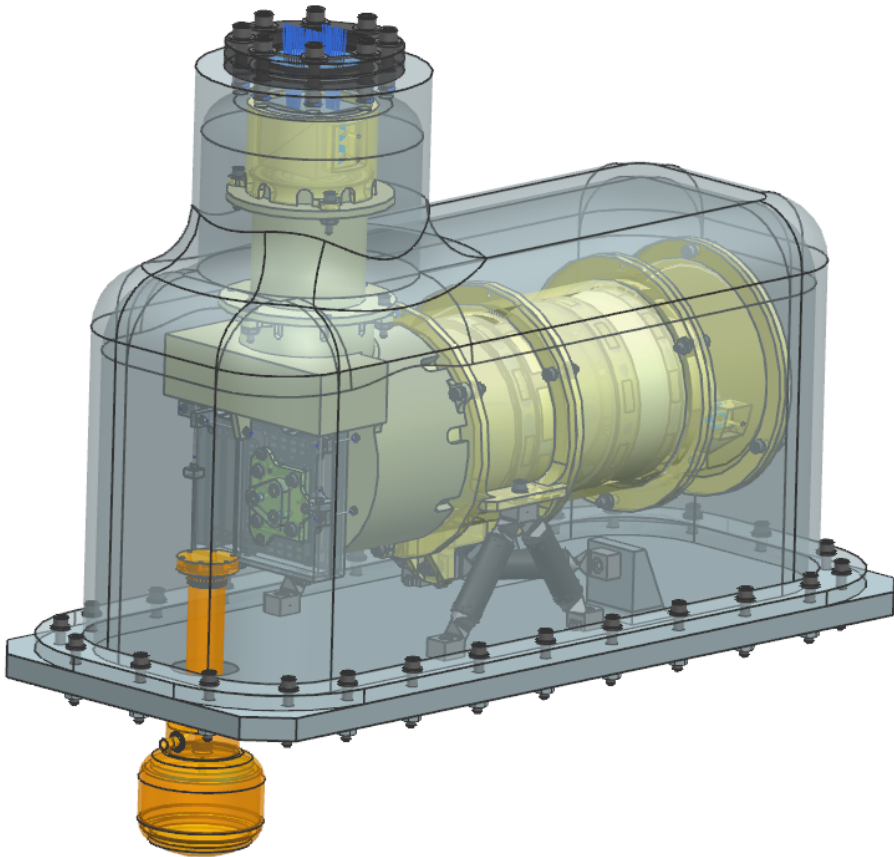
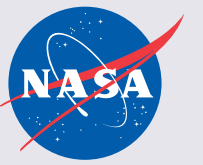


# Instrument 2

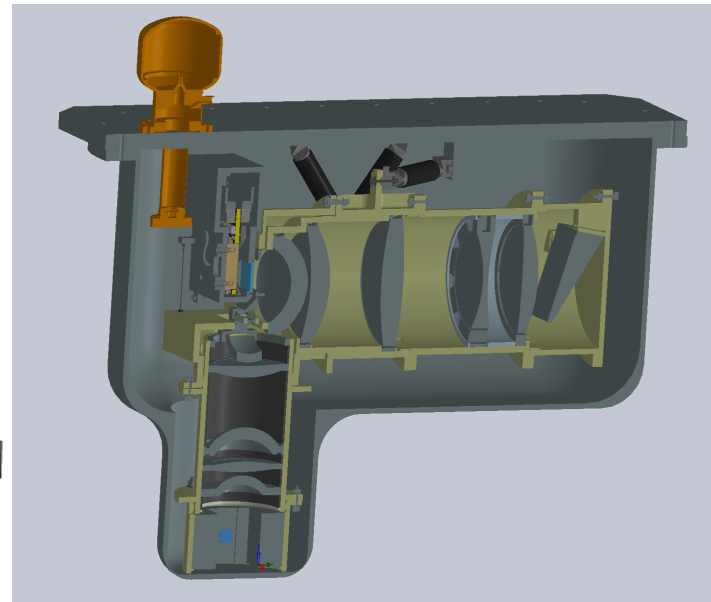
## Optical Design & Optomechanical Packaging



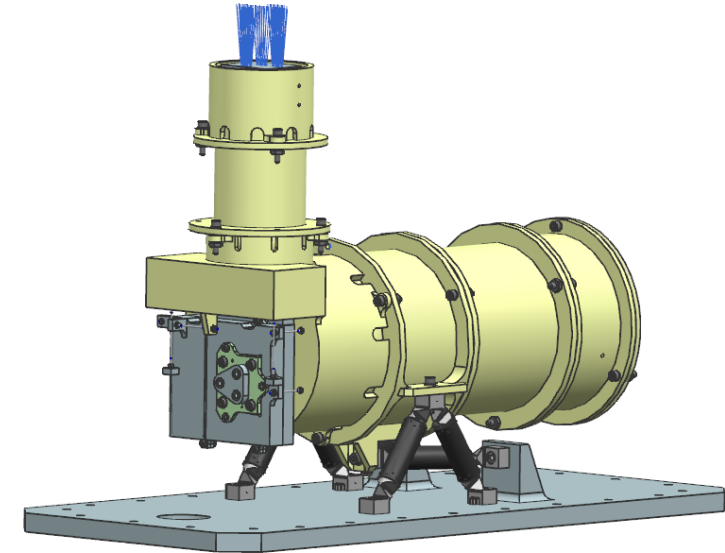
# Instrument 2



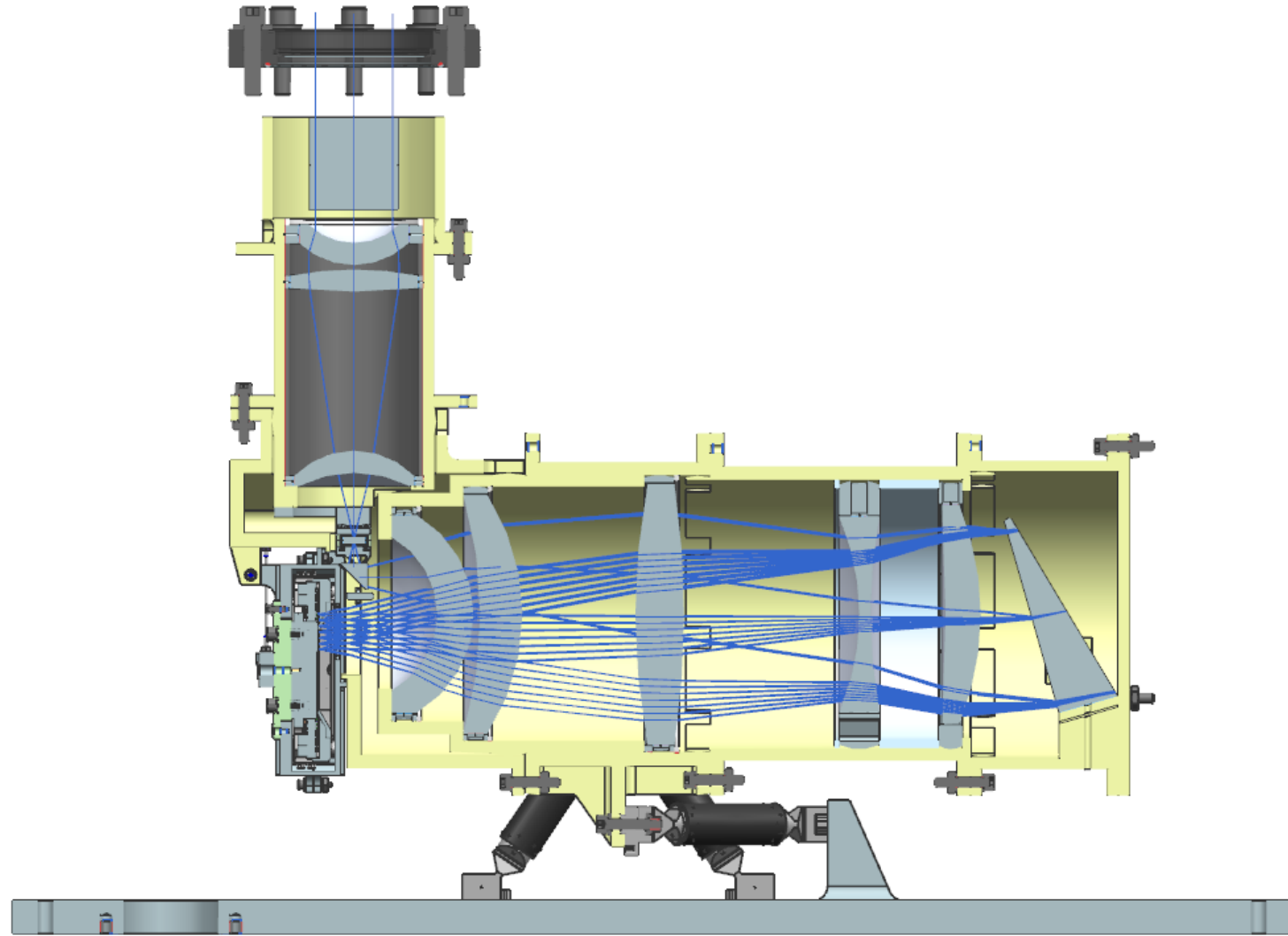
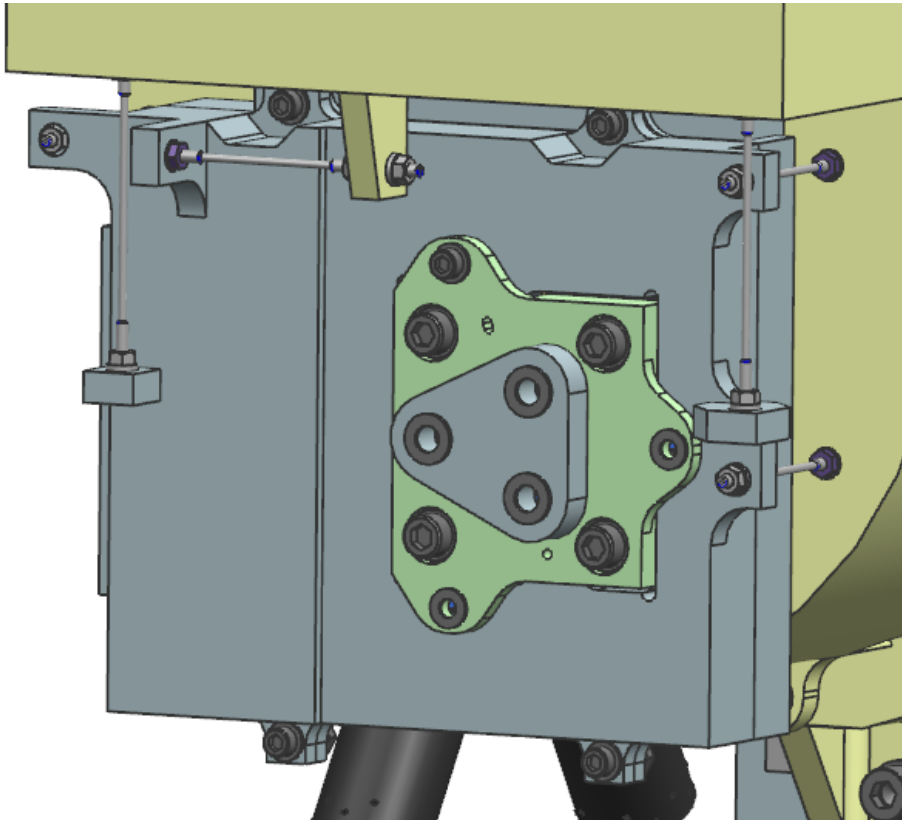
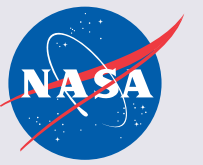
Overall Dimensions: 580  
mm X 260 mm X 526 mm



- Preliminary Thermal Model  
Geometry (4/19/19)

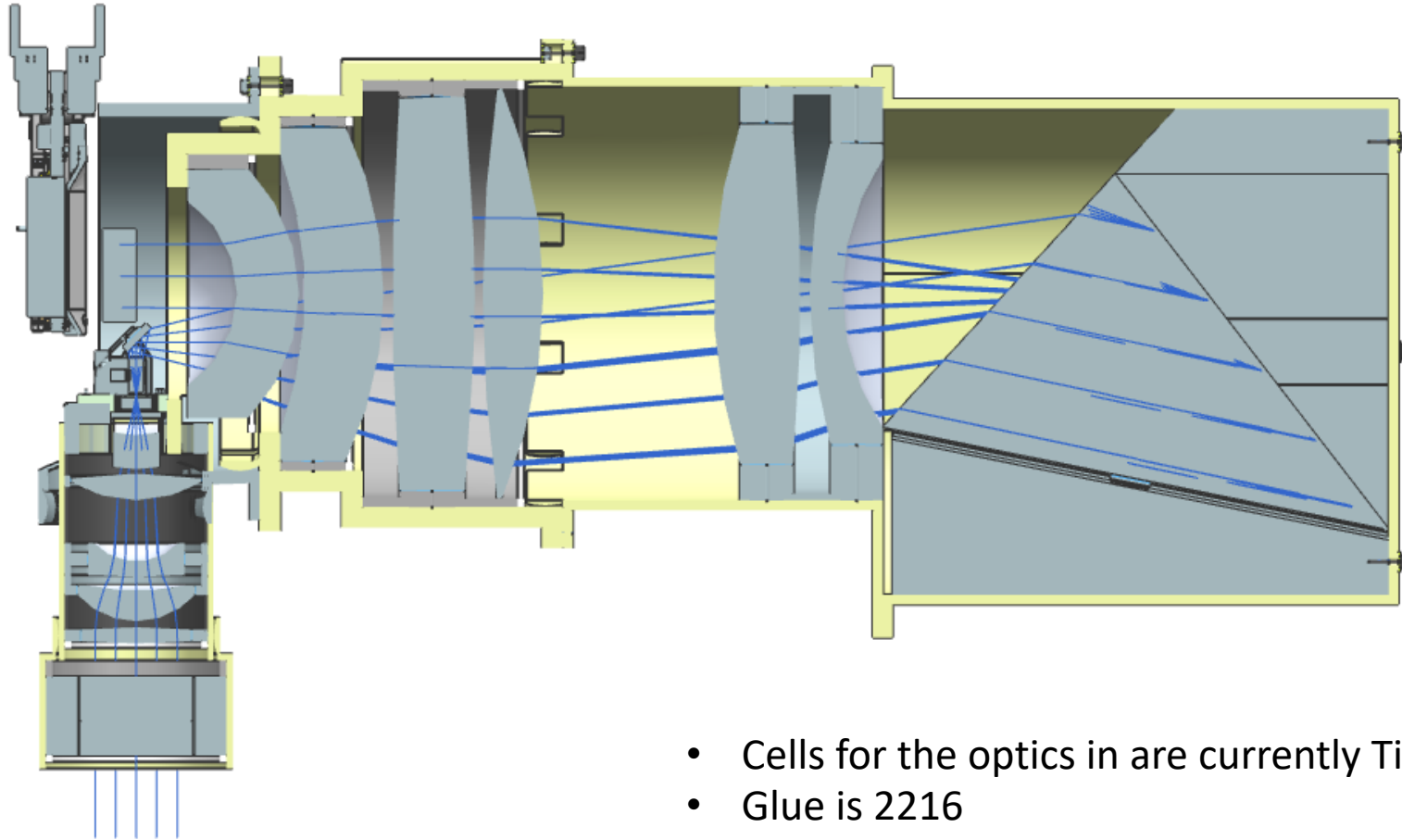
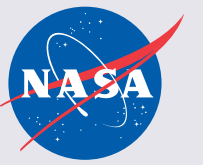


# Instrument 2



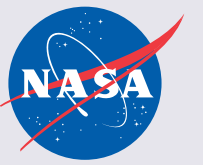
# Instrument 1

## Optical Design & Optomechanical Packaging

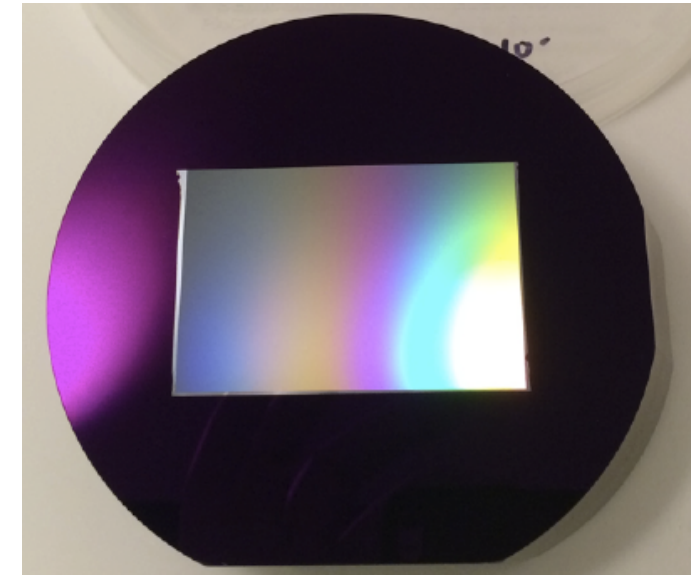
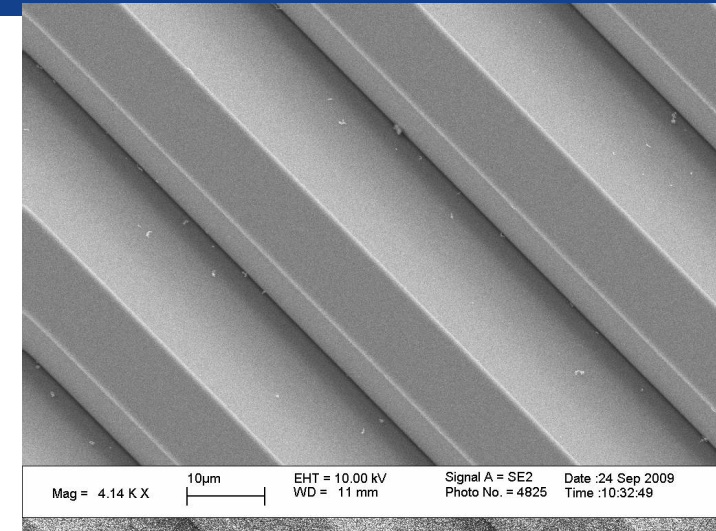
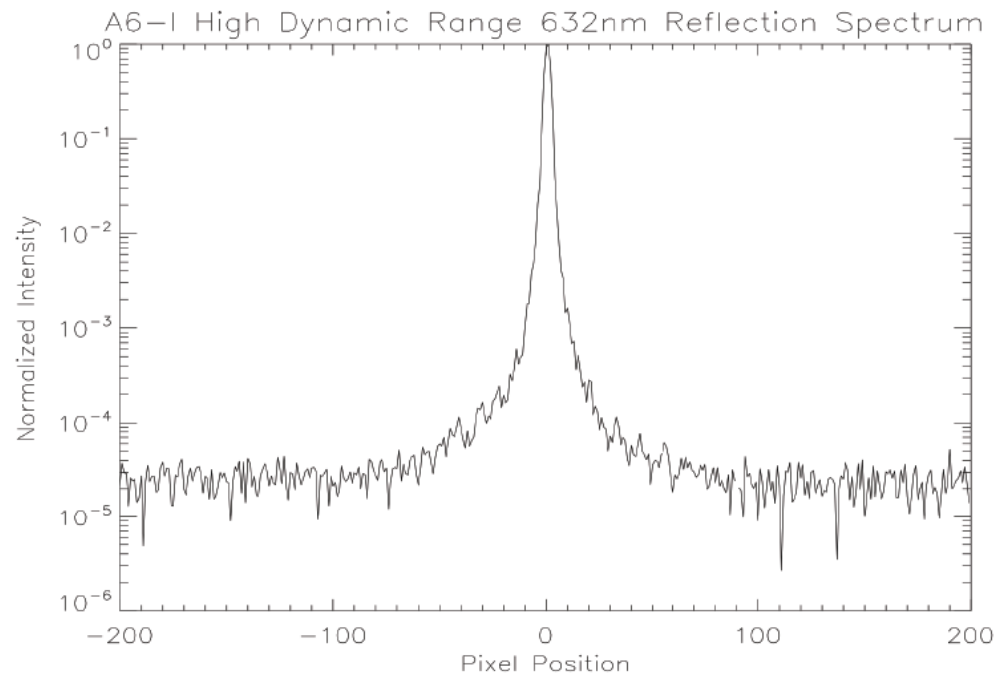


- Cells for the optics in are currently Ti
- Glue is 2216
- Lens Barrel is Al 6061

# CARBO Critical Technology: Si Immersion Gratings

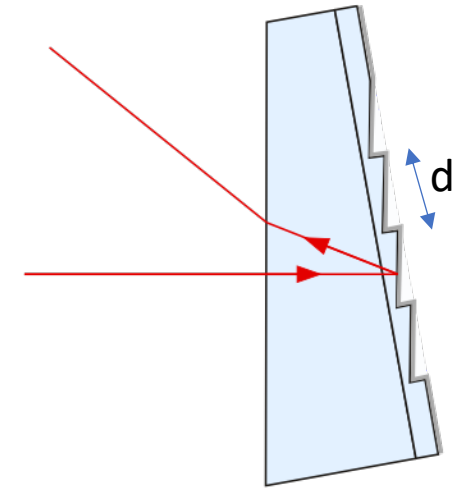


- Si immersion gratings enable CARBO NIR instruments to take full advantage of large format FPAs
- Significantly decreases instrument size
- Up to 15 degree field of view
- Excellent optical performance across entire FPA

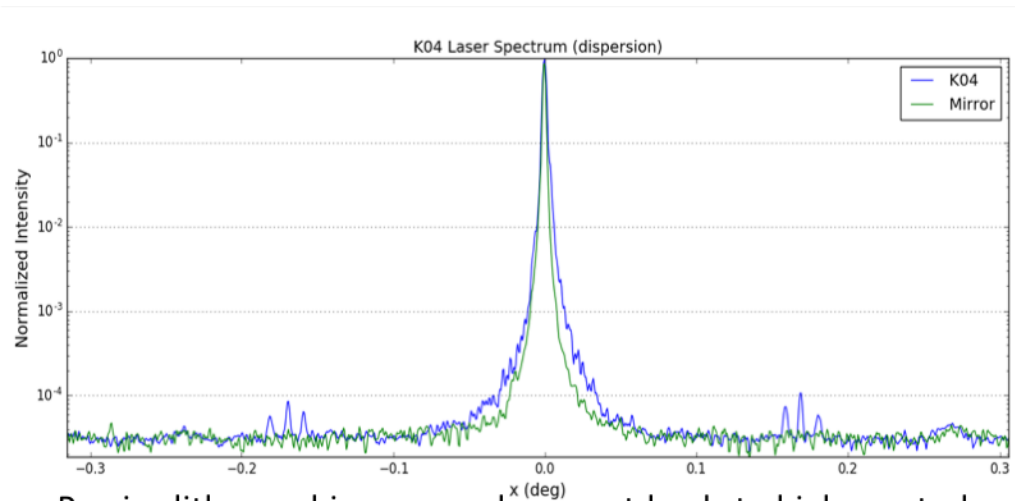


# Key Technologies: Immersion Grating

- Si immersion gratings enable CARBO NIR instruments to take full advantage of large format FPAs
- Significantly decreases instrument size
- Up to 15 degree field of view
- Excellent optical performance across entire FPA

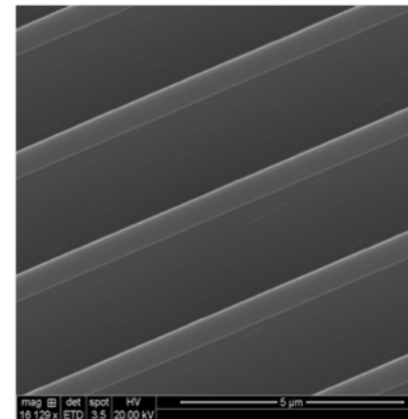


Glass prism with polymer grating



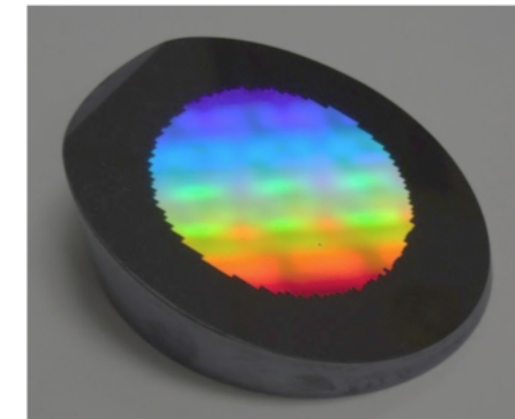
Precise lithographic groove placement leads to high spectral purity.

13 June 2019



Groove structure

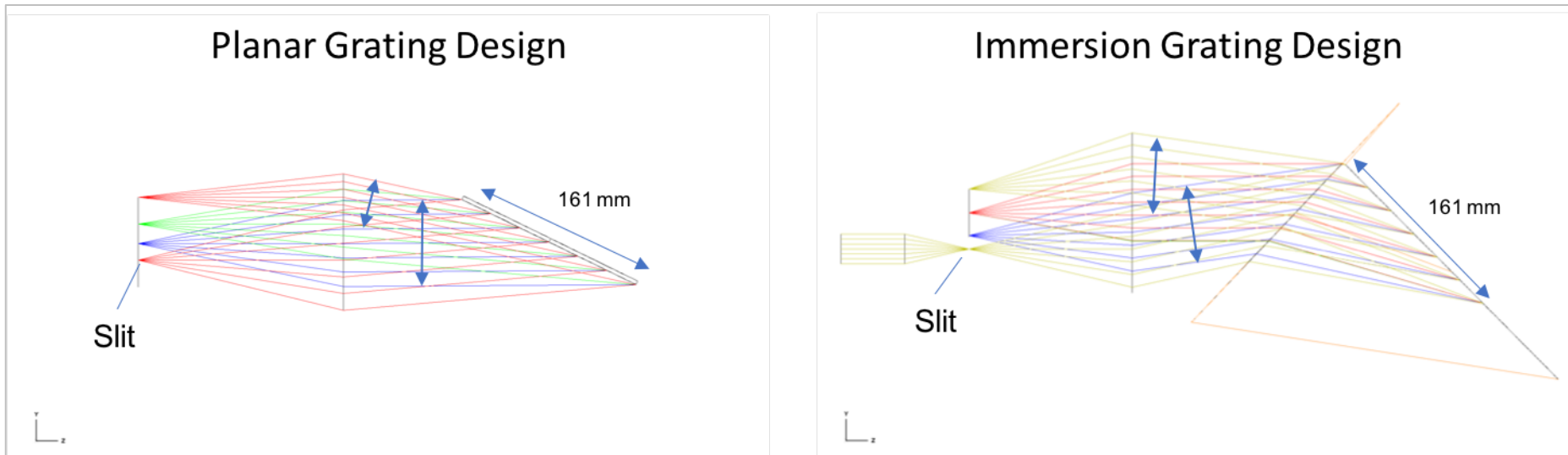
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**Grayscale E-beam Patterned Grating Etched into Silicon Prism**  
(Grating diameter 55 mm, Prism AR-coated on non-grating side)

# Immersion Grating Correction of Anamorphic Compression

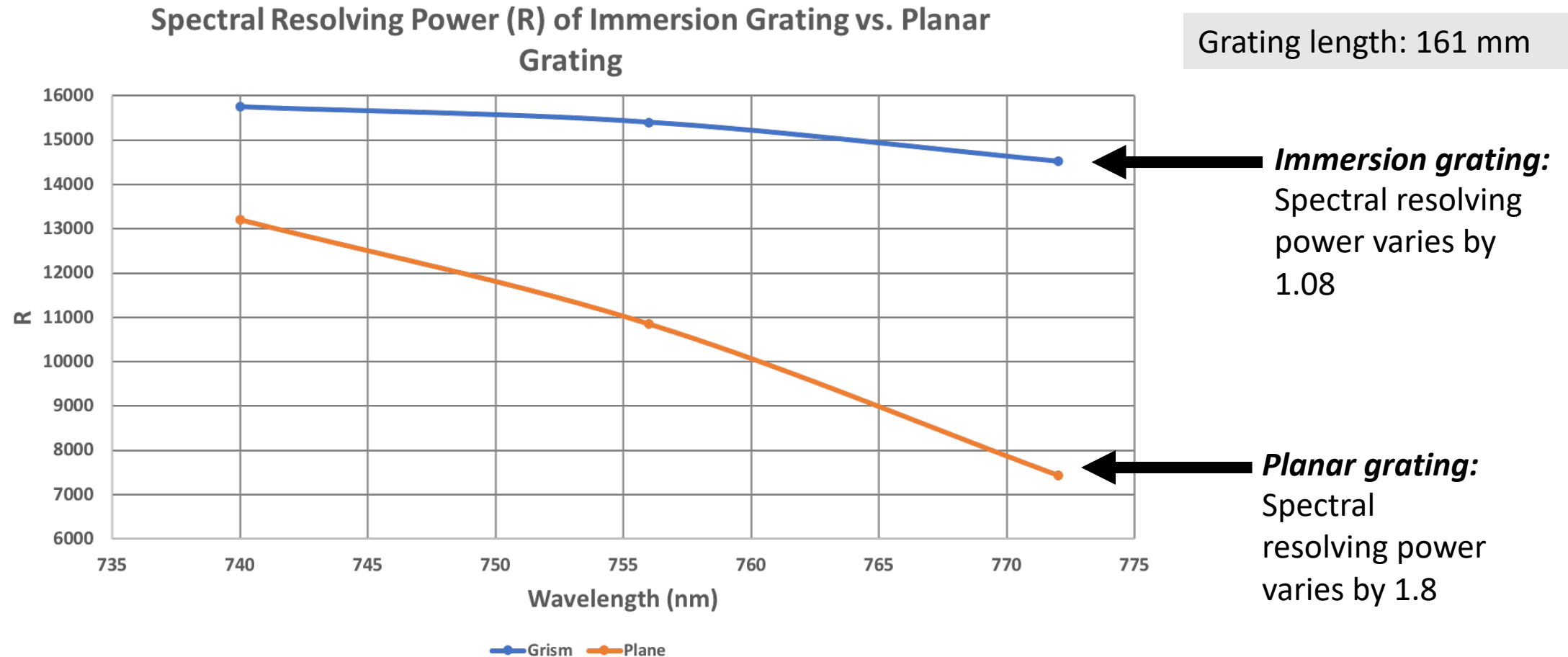
## Immersion Grating Benefit: Reduction in Anamorphic Compression



- A planar grating causes anamorphic beam compression
- An immersed grating can be designed so that the anamorphism is largely compensated by the prism
- Anamorphic correction allows for more symmetric PSF over wavelength, which enables more uniform sampling over the detector

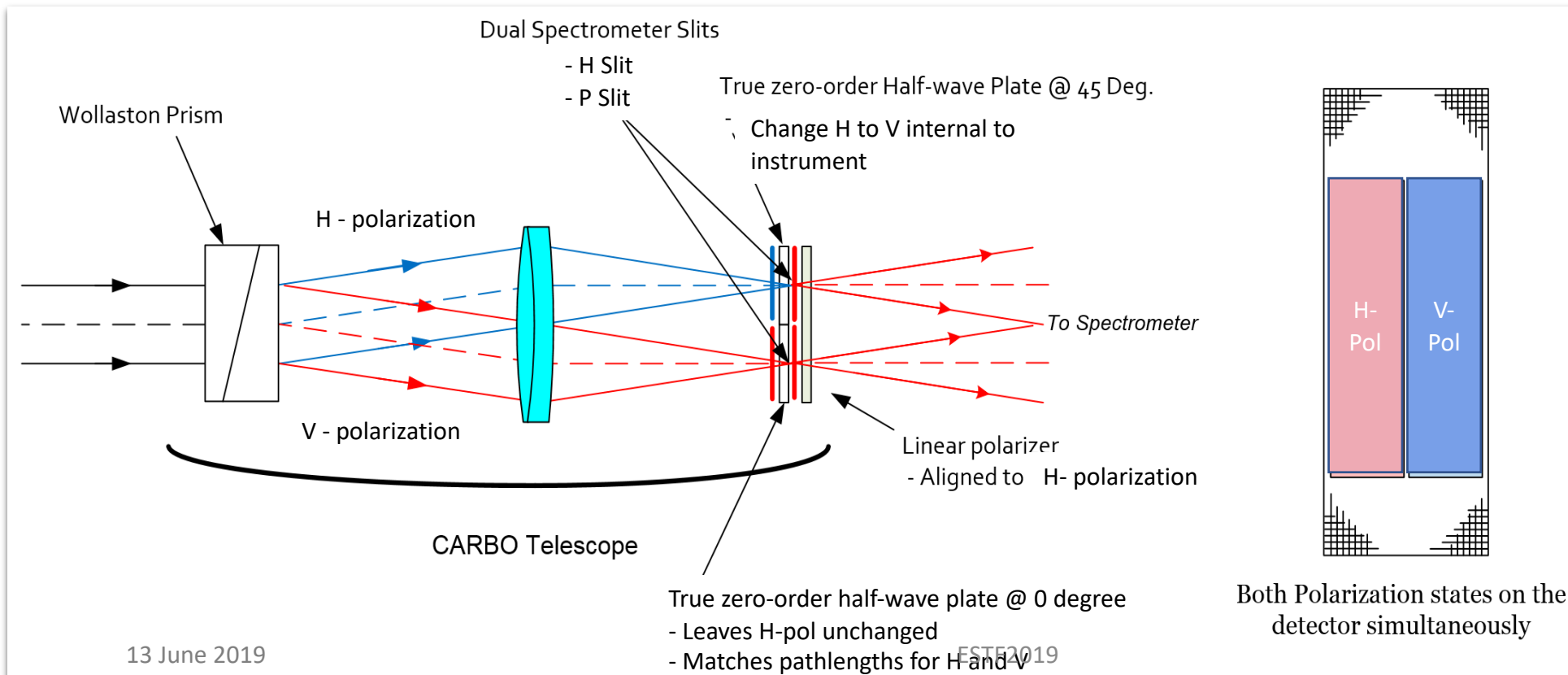
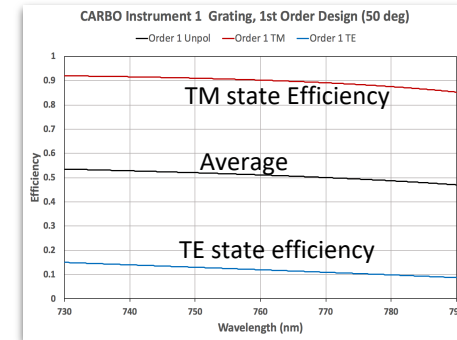
# Immersion Grating and Spectral Resolving Power

## Immersion Grating Benefit: Improvement in Resolving Power Uniformity Across Wavelength



# Key Technology: Simultaneous Polarization Sensing

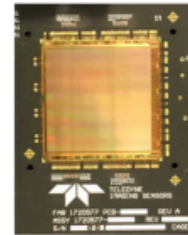
- In general, all gratings are sensitive to polarization states: different grating efficiency for each polarization state → lose photons
- CARBO utilizes an optical design that is insensitive to polarization state, with high grating efficiency
- Enhances sensitivity to surface polarization effects, aerosol composition (better constraints on scattering parameters) and better discrimination of atmospheric and surface scattering.



# New Technology: Large Format FPA CHROMA-D/GeoSnap

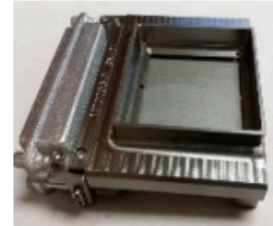
- Latest infrared focal plane technologies from Teledyne Imaging Sensors (TIS)
- 18 um pixel pitch HgCdTe detector hybridized to digital ROIC
- Variable array sizes of 2k x 500 (Chroma-D) and 2k x 2k (GeoSnap)
- Unit cell with 2 gains / full well
  - 100 ke- and 1Me- or 180 ke- and 2.7 Me-
- On-chip digitization
  - without the need for complex analog-to-digital electronics supporting the FPA, the GeoSnap/CHROMA-D allows a simpler overall design for the CARBO instrument
- Snapshot, integrated while read
- Full frame rate: 120 Hz for 2k x 2k






**GeoSnap**  
2K x 2K

ROIC



Focal Plane Module

- ROIC passed radiation tests (no latchup)
- GeoSnap 2Kx2K space flight package developed
- GeoSnap 2Kx2K in production (TRL 6)
- Being used for Visible, MWIR, VLWIR
- CHROMA-D 2Kx512 and 3Kx512 being developed for Earth Science applications

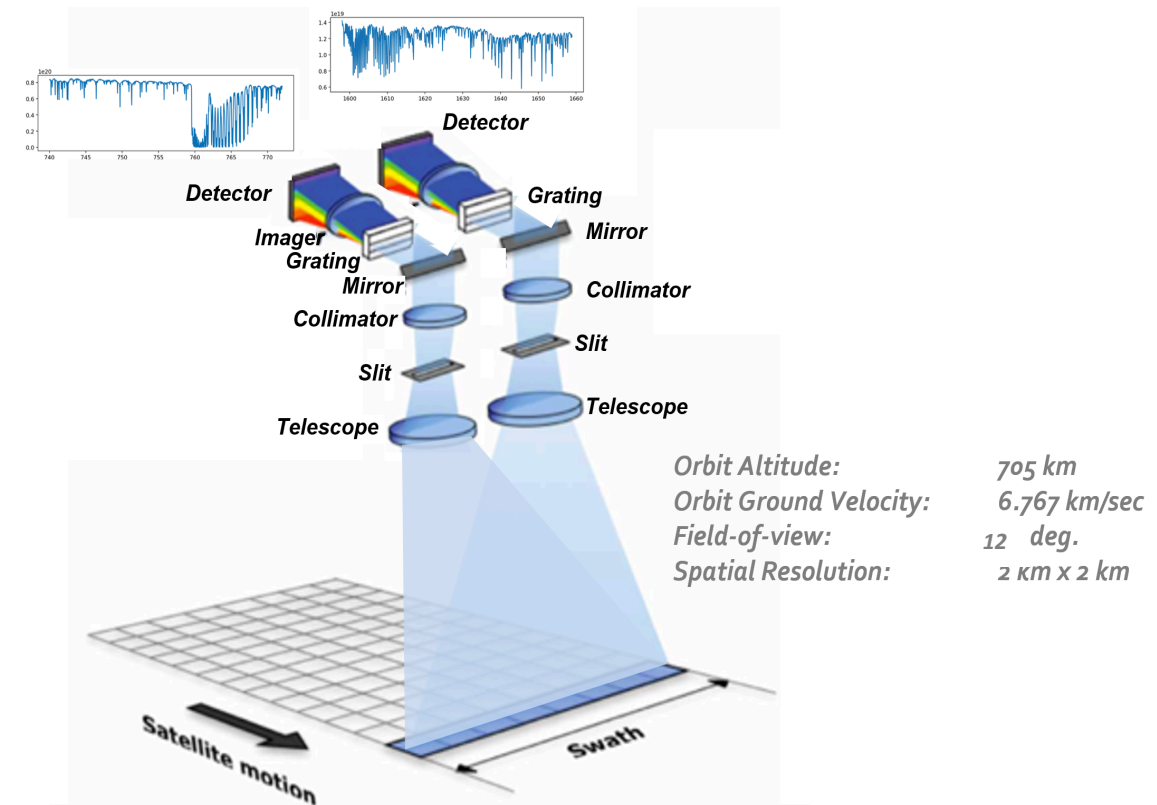


**TELEDYNE IMAGING**  
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# Radiometric Performance Estimate

- The engineering design work is guided by Radiometric performance estimate of signal-to-noise analysis, which is a function of:
  - Radiometry over the band
  - Observational Scenarios (albedo and SZA)
  - Instrument parameters
  - Throughput of the system
  - FPA noise performance
  - Integration time
  - Fabrication constraints



- CARBO is a tech demo instrument, funded by NASA's Instrument Incubator Program (IIP)
- CARBO is modular with a suite of 4 instruments (758nm, 1628nm, 2062nm, 2327nm)
  - Wide-FOV from LEO at 12 degrees (148 km ground swath)
  - CO<sub>2</sub>, CH<sub>4</sub>, CO and enhanced SIF measurements
  - 2x2 km<sup>2</sup> spatial resolution
  - 0.05 nm – 0.15 nm spectral resolution
  - Weekly revisit rate
  - Compact design, common form factor, share one platform
- CARBO advances the following key technologies:
  - Immersion gratings
  - Large format FPA, GeoSnap/CHROMA-D
  - Simultaneous polarization sensing
  - Modular architecture, same form factor, on a common platform
- JPL designs, builds and fields instruments 2, and designs instruments 1, 3 and 4